Effects of a new triple-α reaction rate on the helium ignition of accreting white dwarfs

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Effects of a new triple-α reaction rate on the ignition of carbon-oxygen white dwarfs accreting helium in a binary systems have been investigated. The ignition points determine the properties of a thermonuclear explosion of a Type Ia supernova. We examine the cases of different accretion rates of helium and different initial masses of the white dwarf, which was studied in detail by Nomoto.[1] We find that for all cases from slow to intermediate accretion rates, nuclear burnings are ignited at the helium layers. As a consequence, carbon deflagration would be triggered for the lower accretion rate compared to that of $dM/dt \simeq 4 \times 10^{-8} M_\odot$ yr^{-1} which has been believed to the lower limit of the accretion rate for the deflagration supernova. Furthermore, off-center helium detonation should result for intermediate and slow accretion rates and the region of carbon deflagration for slow accretion rate is disappeared.

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1. *Introduction*   Triple-α (3α) reaction plays an important role for the helium burning stage on the stellar evolution of low, intermediate and high mass stars,[2]–[4] and accreting white dwarfs.[1],[5] Recently, the 3α reaction has been calculated by Ogata et al.,[6] which is very large compared with the previous rate used so far.[5],[7],[8] It should be examined how the new rate affects the astrophysical phenomena, because terrestrial experiments for the 3α reaction are very difficult such as the study of the QCD phase transition at high densities. We investigate the effects of a newly calculated 3α reaction rate (OKK rate)[6] on the helium flashes, which are occurred at the center or inside layers in the accreting envelope of the compact stars. The ignition curves play a critical role when the nuclear burning begins to occur and becomes the main energy source to change the stellar structure, where the fates of the massive stars and/or accreting white dwarfs are determined by the strength of specified nuclear burnings.[1],[9] While nuclear burning depends on the temperature severely, the density becomes very important at high density of $\rho \geq 10^6$ g cm^{-3} and low temperature of $T \leq 10^8$ K, because the screening effects begin to enhance the reaction rates.

It has already shown that the new rate affects significantly the evolutionary tracks of low mass stars for 1 and 1.5 $M_\odot$, where the red giant phase has almost disappeared. As the result, they concluded that the rate is not compatible with observations.[8] We can see the effects of the OKK rate on the stellar evolution with use of the ignition properties. The helium core flash is triggered if the nuclear generation rates (ε_n) overcome the neutrino loss rates (ε_ν) significantly. Figure 1 shows the ignition curves of two 3α reactions and the evolutionary tracks of the central temperature (T_c) against the central density (ρ_c) for stars from 1.5 to 40

$M_\odot$ in the main sequence stages. The evolutions are calculated beyond the core helium burning with the previous 3α reaction rate. We can understand clearly that the helium ignition occurs in the considerably low temperature and density points compared to the previous case.[2),10)]
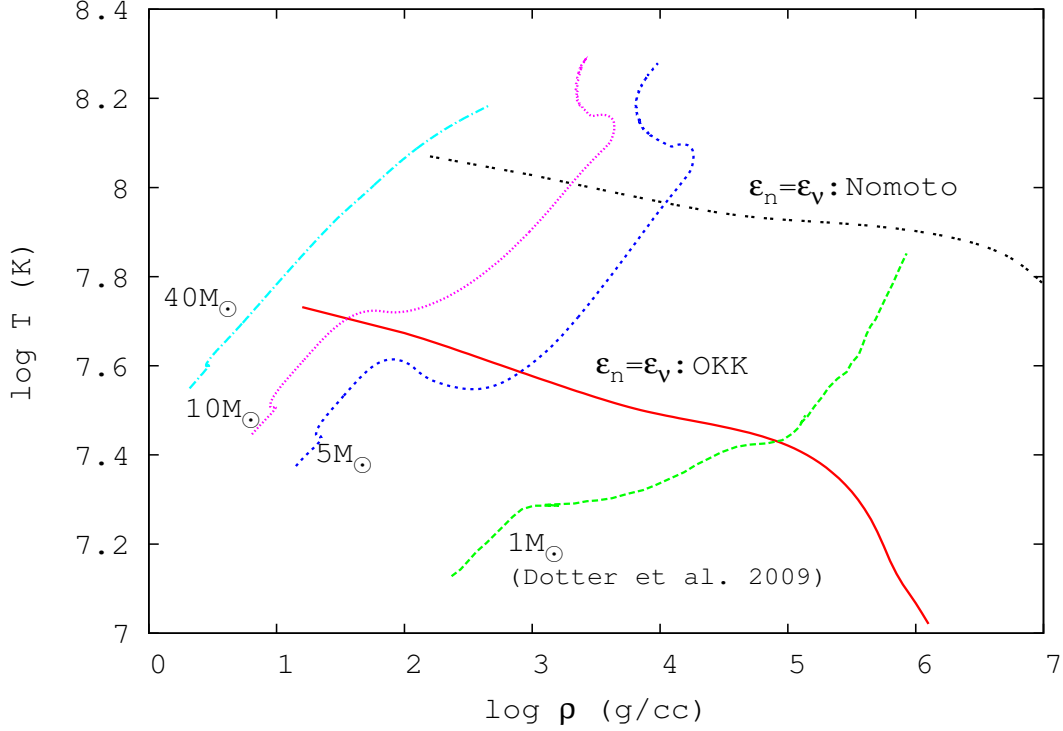

Fig. 1. Two ignition curves of $\varepsilon_n = \varepsilon_\nu$ are obtained from the previous rate (dashed line) and OKK rate (solid line), respectively. Evolutionary tracks of (ρ_c, T_c) with the previous 3α reaction rate are shown for the stars of 1-40 $M_\odot$. For the star of $1M_\odot$, the track is taken from Ref. 8). For other stars, the evolutions are calculated from the zero-age main sequence stage.[11),12)]

2. *Ignition curves and helium flash on the accreting white dwarfs* Accreting white dwarfs are considered to be the origin of the Type Ia supernova explosions.[10)] While the white dwarfs are composed mainly of carbon and oxygen (CO), accreting materials are usually hydrogen and/or helium. Since the hydrogen is converted to helium through steady hydrogen burning, helium is accumulated on the white dwarf gradually and the deep layers become hot and dense. Helium flash triggered in the regions composed of degenerate electrons could develop to the dynamical stage, which depends on the accretion rate dM/dt.[10)] The properties of ignition depend on the initial mass of the white dwarf M_{C+O} for slow accretion rates. If the accretion is rather rapid, $dM/dt \geq 4 \times 10^{-8} M_\odot$ yr^{-1}, the carbon deflagration supernova has been considered to be triggered at the center.[13)] Figure 2 shows the ignition curves concerning the helium flash with the old and new 3α reaction rates adopted, which gives (ρ_c, T_c) for the beginning of the helium flashes. Nomoto[1)] found that the ignition occurs on the condition of $\tau_n = 10^6$ yr, where the time scale of the

temperature increase by the nuclear reaction is defined to be $\tau_n = C_p \, T / \varepsilon_n$ (C_p is the specific heat at constant pressure). Evolutionary tracks of (ρ_c, T_c) for cases A–F are taken from the figures in Nomoto[1] which can be used until the helium flash begins: (cases A–F: M_{C+O} ($M_\odot$), dM/dt ($M_\odot$ yr^{-1})); (case A: 1.08, 3×10^{-8}), (case B: 1.08, 3×10^{-9}), (case C: 1.28, 7×10^{-10}) (case D: 1.35, 7×10^{-10}), (case E: 1.13, 4×10^{-10}), (case F: 1.28, 4×10^{-10}). We can find that the helium ignitions occur in the low density by almost two orders of magnitude if the OKK rate is adopted. Contrary to the results in Ref. 1), nuclear flashes are triggered for all cases of A–F in the helium layers which are accumulated on the CO white dwarfs.
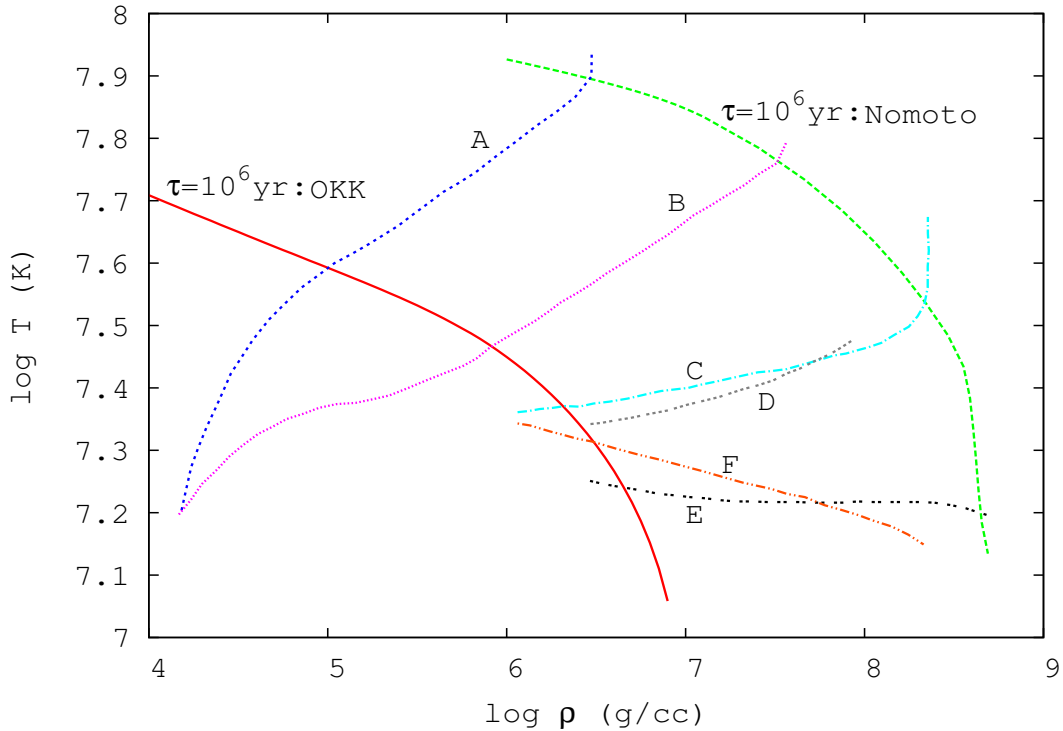

Fig. 2. Ignition curves defined by $\tau_n = 10^6$ yr for the helium flashes on the accreting white dwarfs with use of the two 3α reaction rates. Evolutionary tracks of (ρ_c, T_c) are taken from Ref. 1)

3. *Discussion and Conclusions* The ignition densities that determine the triggering mechanism of Type Ia supernovae will be changed drastically if we adopt a new 3α reaction rate. Although Nomoto[1] has shown that the specific nonresonant 3α reaction is crucial in determining the helium ignition density for accretion as slow as $dM/dt \leq 10^{-9} M_\odot$ yr^{-1}, microscopic calculation for three body problem is found to be much more important to evaluate the 3α reaction rate. Classification due to the accretion rate on the $dM/dt - M_{C+O}$ plane by Nomoto[1] and Nomoto et al.[5] will be changed significantly. It was found that when the density in the burning shell become higher than 2×10^6 g cm^{-3}, the nuclear flash grows into a detonation or deflagration. We emphasize that the accretion rates which induce the carbon deflagration supernova become much lower compared to the standard rate

of $dM/dt \simeq 4 \times 10^{-8} M_\odot$ yr^{-1}.[1),2),5),10),13)] Contrary to the previous calculations, off-center helium detonation dominates the mechanism of Type Ia supernovae for the low helium accretion rate of $dM/dt \leq 7 \times 10^{-10} M_\odot$ yr^{-1} without the carbon ignition at the center. The new rate affects also the helium ignition in accreting neutron stars. In particular, for lower accretion rates, helium burns at lower densities and temperatures, which could change the epoch of a formation of a helium detonation wave and a modeling of Type I X-ray bursts.[5)]

Acknowledgments

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